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Constructing a network of the social-economic consumption system of China using extended exergy analysis

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ABSTRACT

The prominent conflict between consumption and environmental resources is acknowledged as a significant force in affecting the social-ecological community balance. The whole process of resource allocation, utilization, efficiency and outcome are crucial clues in uncovering the structural and functional characteristics in complex consuming systems. Herein, network relationship provides a system-oriented modeling technique for examining the structure as well as flow of materials or energy from an input–output perspective. Meanwhile, extended exergy, the only currently available thermodynamic based metric for social-economic environmental impacts associated with energy consumption, manpower and monetary operation as well as environmental emission, is an extension of the labor theory of value and a possible sustainability metric. The core purpose of this research is to construct a network of the social-economic consumption system of China using extended exergy analysis to explain the interrelationship among different sectors within a thermodynamic metric. Therefore, we firstly make a database of extended exergy accounting in the Chinese consumption system. Data are available for 2007, which can be divided into seven sectors based on the reclassification of the regularly published 42-sector Input–Output Table, namely, (1) Agriculture, (2) Extraction, (3) Conversion, (4) Industry, (5) Transportation, (6) Tertiary, and (7) Domestic sectors. Then we will construct an extended exergy network to gain insight into the thermodynamic distribution within sectoral criterion. Lastly, the network results and indicator analysis are explained for China's social metabolism maintained by a large quantity of energy, resources, and labor, as well as the environmental costs, within an exergy foundation.

Contents

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1. Introduction

Humans extensively consume ecological resources for the sake of supporting social and economic development. However, the over-exploitation and low-efficiency of energy and resource use has led the world to face shortages of the vital natural capital. In addition, the wastes generated from this social and economic production and emitted into the surrounding environments cause ecological pressure on both the regional and global systems. Therefore, it is necessary that we have adequate tools to evaluate the extent of the natural resource shortages, as well as to estimate the ecological impacts for both the scientific and broader communities.

In traditional environmental resource analysis, it is common to value the combination of socio-economic, material, and ecological influence in terms of economic currency and quantity of material flows for the understanding of government and broader communities. However, these monetary valuations lack scientific definition based on energetic or physical explanation. To identify the status, stage, and trend of ecosystem growth and development, a new method, which can value the physical quantity and quality of all socio-ecological processes, is urgently needed in the current evaluation framework.

In contrast to these monetary based approaches, some researchers, particularly those working in the field of ecological economics, have proposed methods to consider all processes and activities in terms of their energetics. In this manner, one can apply first principles such as the laws of thermodynamics, mass balance, and stoichiometry, to socio-ecological problems. Specifically, the concept of exergy, or useful work, provides a unified indicator of different forms of material and energy flows on the basis of evaluating the distance from the studied system to thermodynamic equilibrium [1,2].

Historically, the exergy analysis method was first applied in thermodynamic engineering process evaluation and thermo-chemical system analysis. It can evaluate work based on the Second Law of Thermodynamics instead of general energy flow metrics; therefore, it became a widely accepted method in thermal processing analysis [3,4]. Subsequently, exergy analysis was developed in combination with systems ecology, as a measure of ecological complexity regarding how far the observed ecosystem is from a reference environment [5] and applied to reveal the ecosystem resource availability, buffering capacity, and environmental impacts [6–8]. Therefore, exergy analysis provides a quantifiable method with physical meaning for assessing environmental and ecological degradation.

For the reason that exergy can be used as a consistent measure of material, energy, and information, Wall [1,2] creatively introduced exergy into accounting work of social resource consumption. In recent years, there has been an increasing interest in applying exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving strategies [4]. Within different national and sectoral levels, there are many established cases applying exergy evaluation: (1) For national levels, Japan [9], Sweden [2], Norway [10], America [11], Saudi Arabia [12,13], China [14], UK [15,16], Italy [17], etc. These studies have quantified the exergy embodied available energy flow structure and efficiency for natural resources to assist the country's energy policy and resource management makers. (2) In the social sectoral level, Dincer and his group have published a series of papers in transportation, industry, domestic, public and private sectors [12,13,18,19] to illustrate the efficiency and performance of an exergy analysis of available energy, to evaluate the "resource content" of social-economical input as well as environmental discharges [18,20], and to show several key perspectives of quality, energy conservation, ecological input, economy, environment and sustainable development of subsystem perspectives. Their exergy analysis research results can exhibit the potential usefulness of exergy in addressing and solving environmental problems and moving toward sustainable development, since exergy can characterize the largest amount of energy that can be extracted from material energy. Therefore, unlike energy flow which is only about the quantity, exergy is a measure of quantity and quality of the energy resources.

On the basis of cumulative research on exergy connotations and applications, it is widely acceptable that the exergy-based assessment can be correctly regarded as a physical and thermodynamical based metric in evaluating the scarcity and utility of ecological resources [20–24]. What we want to accomplish in this study is to construct an accounting diagram among social-economic sectors with a network view, to further apply exergy theory in revealing its available energy capacity and metabolic interrelationship within a sub social-economic system level. However, in view of the varied social and economic impacts from energy and resource use within the whole social system, we need a more extensive and inclusive metric to account for the intrinsic (money and primary resources) expenses and social (money and services) "payback" in different social levels. Meanwhile, for the human dominated society, systematic accounting of social exergy flux, is a comprehensive, synthetical, and unified metric for ecological and social factors, which can reveal the natural wealth in the process of socio-economic diagnoses and decision making. It does, therefore, provide biophysical-based scientists and economists a measure to minimize leading to sustainable development and social-economic-ecological harmony.

Therefore, in recent years, nonmaterial energy resource elements, labor production factors, and economic parameters have been incorporated into the horizon of exergy research. This approach is called Extended Exergy Accounting (EEA) [21]. EEA is an "embodied" measure for the total primary exergy resource equivalent consumption [22,25]. It is an extension of traditional exergy analysis by including socio-economic factors such as labor and capital costs in physical terms of the equivalent primary resource consumption. EEA had been revised and published in a series of theoretical research and applications issues [21,22,24,26]. The intrinsic measurement of extended exergy (EE) is the amount of primary exergy homogeneously expressed in Joules that being cumulatively used over the production, operation, and disposal process. EEA includes four basic parts: (1) the standard material and energy primary resource exergy (quantified by their respective cumulative exergy content), (2, 3) labor and capital (two social, economic factors), and (4) environmental remediation costs. The latter three parts represent the primary resource cost equivalent of the so-called "externalities". The advantage of EEA is that it is much easier and more meaningful to compare within one unified and rational criterion different commodities and different production processes [27]. As an extension of traditional exergy analysis, EEA is widely accepted as a comprehensive method based on the concept of a physical cost based not only on a monetary proxy, but also on the equivalent

primary resource consumption. Furthermore, such an effective measure of natural-social-environmental impacts can be considered in some sense as the real "ecological cost" of all material and energy resources, human labor, capital, and environmental remediation costs related to a certain system. Thus, EEA considerations provide a vivid and global understanding of the physical, thermodynamic, economical and ecological costs that bridges the gap about the 'production of value' which separates most economics and biophysical-based approaches [28,29].

In a nutshell, EEA is a socio-economic construct with biophysical references, intended to bring the labor theory of value and the current thermodynamic theory into harmony, so that the "extended exergy cost" (i.e., the equivalent amount of primary resources required for the production of a commodity) can be used as a goal function to optimize the allocation and distribution of the involved "values" (meaning "use values" in this study). Since the quantifier is the primary resource base, it is possible to use EEA to propose and explore scenarios aiming at development of a society towards reduction and improved efficiency of long-term exergetic resource consumption. Given the current unsustainable state of affairs, EEA can be considered as a proper tool to measure the cost to decrease our degree of unsustainability: it does so not only by displaying the loss of available energy at each step of a productive chain, but also supplying input conditions and allocations, for "more sustainable" solutions may in some cases require greater resource consumption than "less sustainable" ones [30]. Furthermore, new light is shed by EEA on the so-called "environmental externalities quantification" problem, in that this theory associates the internal irreversibility of a system not only with material- and energy use but also with its waste emissions.

The whole process of resource allocation, utilization, efficiency, outcome and environmental impacts are crucial clues in uncovering the structural and interrelationship characteristics in complex consuming systems, both exergy generation and consumption processes contain large exergy flow distribution as well. Herein, we construct the exergetic network relationship of the Chinese socio-ecology to provide a system-oriented modeling technique for examining the structure as well as flow of materials or energy from an input–output perspective.

For an integrated system, different subsystems have variable exergy supply–demand relations and play diverse roles in maintaining social life and human requirements. To analyze the exergy and extended exergy flow characteristics in a systematic and structural perspective, we need to decompose different flows within a whole social and economic system boundary. However, judging from the present existing studies, analyses of the inherent structure and functions of the social resource metabolism are lacking a systematic basis and network perspective. Furthermore, to optimize the structure by measuring and adjusting the relationships among compartments, it is necessary to use ecological based network analysis for national social-economic ecosystem research. In this study, we chose Ecological Network Analysis (ENA) as the methodological approach. ENA, the more general version of network analysis, has been recently proposed as a generic tool for systematic and functional assessment in the context of ecosystem-based management [31–37]. Meanwhile, the truth that it can encounter flow incompatibility in a material- or energy-oriented ecosystem remains impeditive when evaluating different flow configurations. Energy and material, the conventionally used units for network analysis, are widely acceptable and adaptable for exergy and extended exergy based analysis.

In this study, to be congruent with the theoretical requirements and internally consistent, we first provide a concise overview of the exergy origin, and its development and application, followed by the current status of extended exergy to include social economic factors. The rest of the paper is organized as follows: (1) An illustrative example is given to demonstrate how extended exergy accounting can be applied in a more realistic and meaningful assessment than the conventional energy analysis of the efficiency and performance for a flowing and consuming system. (2) To study the whole resource consumption and allocation system, to analyze the resource flow metabolism and its corresponding input–output relationship within system and subsystem levels in China 2007, by means of the extended exergy analysis to investigate the status of material and energy use, social and economical input, and the environmental impact of waste pollution and control cost. (3) Finally, on the basis of above China EEA, we construct a network of the social-economic consumption system.

2. Methodology and data

2.1. EEA

As stated above, the unique feature of EEA is that it is a composite measure of the material thermo-mechanical and chemical exergy values plus the labor and capital inputs and environmental remediation costs all expressed in energetic units (joules). The procedure for converting all pieces to a common dimensional quantity is given below. The calculation of the *EE* of a generic (material or immaterial) commodity is formulated as follows:

$$EE = CEC + E_K + E_L + E_R \tag{1}$$

where *CEC* represents the cumulative exergy consumption of material flows as defined by Szargut [38], E_K is the exergy equivalent of capital flows (or active monetary circulation), E_L is the exergy equivalent of human labor, and E_R stands for the environmental impact or remediation cost.

In Eq. (1), *CEC* expresses the cumulative exergy consumption (including both primary resources consumption and secondary semi- or completed-manufactured material input). From a consumption viewpoint, *CEC* consists of three distinct portions:

(1) The direct "energetic" natural resources input (coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, etc.), which are quantified by their respective *CEC* transformation factors (listed in Section 3, Fig. 4), which are of the same order of magnitude as their lower heating values [38].
(2) The "secondary energy resources", like electricity, heating energy, etc.: They are quantified by their respective *CEC* transformation factors (also listed in Section 3, Fig. 4).
(3) The natural exergy consumed, and therefore "embodied" as a cost, in all manufactured (material) good transport equipment consists of vehicles, batteries, engines, airplanes, etc. and their components. An average value for each one of these flows was calculated for the year under scrutiny and the total was included in the balance as an exergy flow from one sector to another sector.

Exergy factors of fossil fuel can be acquired from [38,39] which are summarized in Fig. 4, and all physical data have been extracted from [40,41] shown in Figs. 4 and 5. In order to show the *CEC* input clearly, we combine the second portion and the third portion together, namely the "secondary energy resources" and "embodied cost exergy", as the non-direct natural resource exergy input and label this as *CEC-2* (see Fig. 1).

For each sector in this research, we establish a commonly used EEA model to show the EEA structure and accounting boundary in Fig. 1.

In Fig. 1, *CEC-1* refers to the ecological resource directly from environment; and *CEC-2* is the exergy input from the other sectors,

for example, the processed goods, instruments, secondary materials, etc.; and E_{in} will be explained clearly in the following part.

2.2. Converting labor and capital into exergy

EEA is based on two major postulates: first, that E_{in} (the global influx of exergy resources into a society or community) is primarily used to sustain the total population of the society in order to generate labor; second, that the equivalent exergy flux required generating the capital circulation $M2$ is proportional to the EE of labor:

$$E_L = \alpha \times E_{in} \tag{2}$$

$$E_K = \beta \times E_L \tag{3}$$

In [19,20,27,43–46] the expressions for α and β are

$$\alpha = \frac{f \times e_{surv} \times N_h}{E_{in}} \tag{4}$$

$$\beta = \frac{M2}{sN_W W} \tag{5}$$

where f is correction factor related with the life standard level in a certain social system (f=HDI/HDI$_0$, HDI is Human Development Index of life expectancy, wealth and education used in socioeconomics published by the United Nations every year); e_{surv} refers to the exergy consumption for human survival; N_h is the total population in the study system; $M2$ is the amount of money stock in a certain year ($M2$ stands for purchasing power, in China a large portion of the $M2$ is in time and saving deposits, which is not the monetary circulation in accordance with those of the western bank system, and also checks cannot be freely cashed as it is in the western countries. Therefore, and only for this reason, we were forced to take the GDP as the monetary circulation indicator); s is average wage; N_w is the number of workers; W is the average workload. In Eqs. (4) and (5), α and β introduced here represent the fraction of the primary exergy embodied into Labor and the fraction of the Labor exergy embodied into Capital, respectively. Here are all the parameters used in the whole accounting process (Table 1).

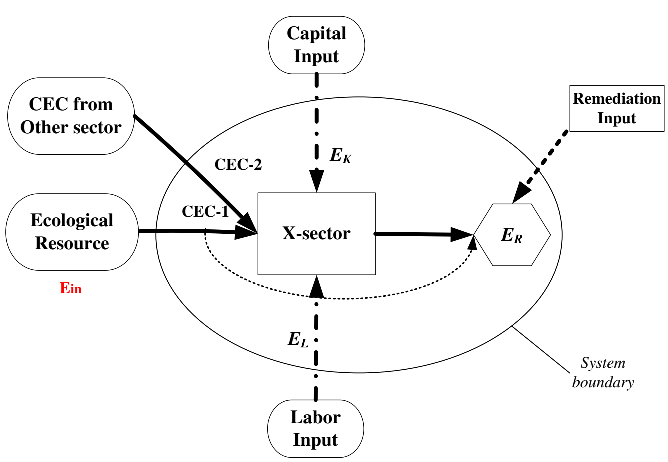

Fig. 1. EEA accounting boundary for each sector in this study.

2.3. E_R evaluation method

The possibility of using exergy as a measure of potential to cause environmental change has been debated for a long time, because exergy cannot characterize the extent of environmental toxicity or impacts, such as greenhouse effects, eco-degradation, etc. However, EEA takes a completely innovative strategy to explain the treatment of pollutants: it calculates the added equivalent exergy caused by primary resource consumption by an implemented or proposed treatment process to remove the emitted pollutant. This environmental emission equivalent exergy can be regarded as the "environmental externalities" or "environmental disturbance".

To apply this method, the exact amount of each (material or immaterial) "emission" must be known together with its exact chemical composition, when relevant in the whole system. These data are partly absent in the available database for the Chinese society, and therefore, for the existing emission detailed lists we can calculate their chemical exergy as the environmental influence exergy, and for the absent part emissions, the monetary yearly expenditure for environmental remediation and management $E_{RC'}$ (which is available in the database) was converted into an equivalent extended exergy environmental cost $E_{R'}$ as follows:

$$E_{R'} = E_{RC'} = ee_K \times I_{env} \tag{6}$$

$$ee_K = \frac{\alpha\beta E_{in}}{M2} \tag{7}$$

where ee_K is the specific exergy equivalent of the monetary unit, and I_{env} is the monetary rate of investment in remediation measures. This is not exactly in line with the original EEA formulation, in which the environmental remediation cost is calculated on the basis of a real or ideal process in which the effluents are treated [47]. Such a calculation is impossible for the present case study. Our assumption

Table 1
List of the parameters used in the evaluation of α and β.

Parameter	Unit	Value (for China, 2007)
f	/	13.75
e_{surv}	J/(person × day)	10^7 J/(person × day)
N_h	Population	1.33×10^9
E_{in}	J/yr	Total ecological resource exergy input into the system
$M2$	RMB/yr	*GDP* (3.03×10^{13} RMB)
s	RMB/yr	Depends on different sectors or system
N_w	Population	Depends on different sectors or system
W	Workhours/(person × yr)	2000 h/(person × yr)=8 h/day × 250 day/year

Note:
1. HDI$_0$=0.055, e_{surv}=107 J/(person × day) [27];
2. HDI (2007, China)=0.756 [41,42];
3. N_h=1.33 × 109, GDP=3.03 × 10^{13} RMB [40]; W=2000 h/(person × yr) [28];
4. E_{in} will be calculated in the results, s and N_w can be collected in [50];
5. GDP is used as a quantifier of the monetary circulation. Its numerical value is different from the real monetary circulation; Even conceptually the *GDP* is not a correct indicator of monetary circulation, because it merely represents the monetary measure of the goods and services generated, imported and exported.

must be viewed as an approximation due to data shortage, which provides another approach others with data scarcity may apply.

2.4. System boundary

The societal accounting initially proposed by Wall [1] focused on the cross-section from the resource base to end-use sectors: it followed indirectly the approach originally suggested by Szargut [48], and was improved by Ertesvåg [10] and Milia and Sciubba [49], who divided the society into seven subsystems interacting with their environment and labeling all fluxes of matter and energy in a metabolic-like process. Later, Chen et al. [19] established a pyramidal scheme consisting of seven sectors, aiming at revealing the exergetic consumption structure of the society. In this study, we further modified the framework to show the extended exergetic structure of the society corresponding to the special socio-economic characteristics of the society, and the societal system was subdivided based on the Input–Output (IO) Table in 2007 in China. The IO Table is known as a balanced sheet, reflecting the interactions between various sectors within a certain period based on material and its corresponding currency flows. The IO Table is divided into physical form and economic value form, respectively, based on different measurement units. We choose economic value date in this research with the purpose to unify the embodied physical exergy flows from different types of primary and secondary products and services between different sectors under a certain productive technology level. Meanwhile, in order to simplify the complexity of the whole system and clarify the interactions between economic sectors based on an ecological trophic and network structure, we aggregate the 42 subsectors into seven main sectors of the social and ecological exergy flow system partly in the consideration of the previous research and functional similarity of different subsectors. New classification contents are shown in Table 2.

According to the resource input and flow distribution processes, an exergy based sectoral hierarchy system chart is described here to

Table 2
Classification of total sectors used in this study number each subsector from the original.

Sector (7)	Content	Subsector (42)
Extraction (X1)	Extraction, including mining and quarrying, oil and natural gas, refining and pre-processing	Mining and Washing of Coal (02) Extraction of Petroleum and Natural Gas (03) Mining and Processing of Metal Ores (04) Mining and Processing of Non-metal Ores and Other Ores (05)
Conversion (X2)	Conversion of primary energy and materials into heat, power and electricity	Production and Supply of Electric Power and Heat Power (23) Production and Supply of Gas (24) Production and Supply of Water (25)
Agriculture (X3)	Harvesting, forestry, animal husbandry, fishery, water cultures, and food processing	Agriculture, Forestry, Animal Husbandry, Fishery (01)
Industry (X4)	Industry, manufacturing industry except oil refineries	Manufacture of Foods and Tobacco (06) Manufacture of Textile (07) Manufacture of Textile Wearing Apparel, etc. (08) Processing of Timber and Manufacture of Furniture (09) Manufacture of Paper, Printing, Articles, etc. (10) Processing of Petroleum, Coking, Processing of Nuclear Fuel (11) Chemical Industry (12) Manufacture of Non-metallic Mineral Products (13) Smelting and Pressing of Metals (14) Manufacture of Metal Products (15) Manufacture of General, Special Purpose Machinery (16) Manufacture of Transport Equipment (17) Manufacture of Electrical Machinery and Equipment (18) Manufacture of Communication Equipments (19) Manufacture of Measuring Instruments etc (20) Manufacture of Artwork and Other Manufacturing (21) Recycling and Disposal of Waste (22) Architecture Industry (26)
Transportation (X5)	Transportation services	Transport, Storage (27) Post (28) Information transfer, Computer Services and Software (29) Wholesale and Retail Trades (30) Hotels and Catering Services (31) Financial industry (32) Real estate (33) Rent and Commercial Service Industry (34) Research and experimental developing Industry (35)
Tertiary (X6)	Tertiary, including construction and real estate	Integrated technical service (36) Management of Water Conservancy, Environmental and Public Establishment (37) Neighborhood Services & other services (38) Education (39) Sanitary, Social Security and Public Welfare (40) Culture, sports and entertainment industry (41) Public management and social organization (42)
Domestic (X7)	Domestic sector, households	Rural consumer expenditure (final consuming) Urban consumer expenditure (final consuming)

show the extended exergy input–output procedure and its allocation within seven sectors (see Fig. 2).

In this picture, full lines refer to exergy flow based on material resource deliver among different sectors, dotted lines are labor and capital exergy which are the productions of Domestic sector after substantial resource consumption.

The interactions between economic sectors could be depicted in a network, which is analogous to an ecological trophic structure. In order to decompose every exergy input and output flow among the seven sectors, we make a pyramid structure with three different trophic levels to unequivocally illustrate each extended exergy accounting step in the whole system (see Fig. 3). First of all, Extraction, Conversion, and Agriculture are the first three sectors gaining ecological resource (E_{in}) directly from natural surroundings. Secondly, the primary process, exergy embodied in energy resource (*CEC-1*) is invested into second level sectors for further manufacturing and sub-treating, after which the different types of products and services are generated. Third, the exergy embodied in products and services' costs (*CEC-2*) are input to the other sectors for subsequent handling and value creating. The last step, Domestic sector is regarded as a final consumption sector, which occupies all the ultimate system embodied resource exergy for the sake of delivering labor and capital (E_L and E_K) to the whole system. In addition, environment emissions (E_R), the disturbance to previous environmental and ecological equilibrium, always exist during the whole process of material resource depletion.

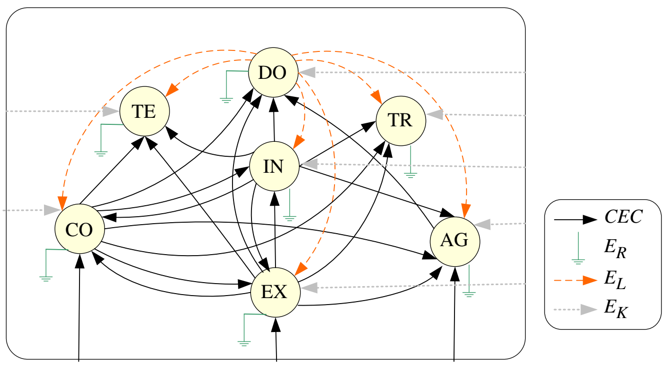

Fig. 2. System diagram for sectoral metabolism hierarchy extended-exergy flows where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic.

3. Results

3.1. EEA in seven sectors in China (2007)

3.1.1. CEC accounting

Table 3 shows the *CEC* ingredients' list for seven sectors: for the natural resource part, *CEC* can be evaluated on the basis of cumulative exergy consumption as defined by Szargut and the transformation factor for different resource types [38].

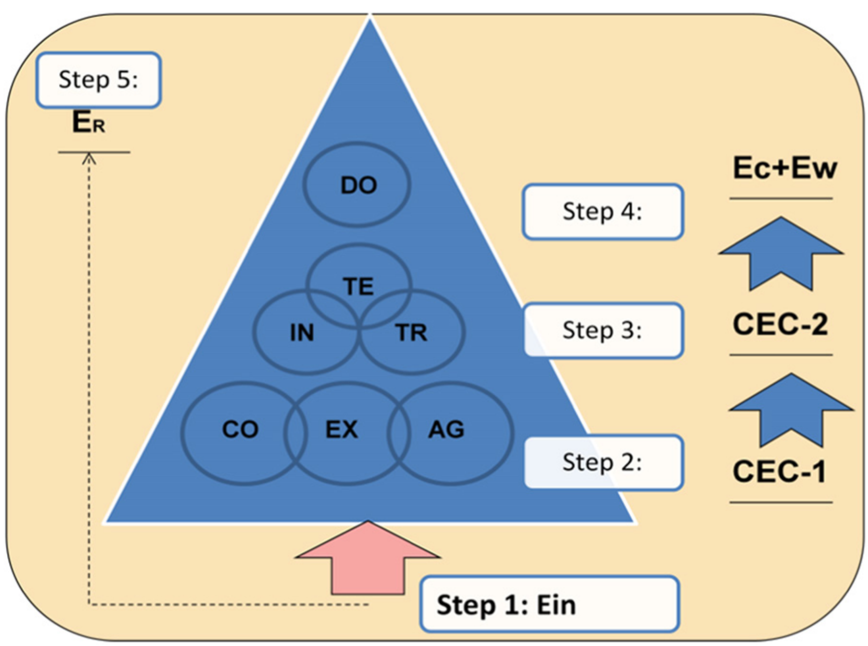

Fig. 3. An ecological trophic structure of interactions between seven economic sectors based on extended exergy accounting where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic.

Table 3
CEC accounting ingredients in seven sectors in China (2007).

Sector	*CEC* ingredients
EX-sector	Fossil energy, electricity, metals, inorganic minerals, input from other sectors
CO-sector	Fossil energy, electricity, hydropower, thermal power, nuclear power, input from other sectors
AG-sector	Fossil energy, electricity, farm products, forest products, livestock products, aquatic products, input from other sectors
IN-sector	Fossil energy, electricity, input from other sectors
TR-sector	Fossil energy, electricity, input from other sectors
TE-sector	Fossil energy, electricity, input from other sectors
DO-sector	Fossil energy, electricity, input from other sectors, farm products, forest products, livestock products, aquatic products

For the input–output (equivalent to production–consumption relationship) exergy in E_{in} and *CEC-1* accounting, primary substantial resource exergy has been accounted in Tables 4 and 5. However, the secondary resource exergy flow from one sector to another, embodied as the cost of products and services, is calculated by means of IO Table. Here are the original economic data (Table 6-a) and accounting results (Table 6-b). The empty value is in *CEC-1* accounting showed in the previous part.

3.1.2. E_L and E_K accounting

According to China Labor Statistical Yearbook [50], the economically active population was 786.45 million, in which the real employee number was 769.90 million. Based on these social and economic data, we calculate the values of the important two *EE* factors α and β are 6.12×10^{-2} and 4.87×10^{-1}, respectively, for China in 2007. Meanwhile, labor productivity is assumed to be non-discriminatory between different individuals within a certain period. The employee's sectoral distribution and salary difference as well as the final human embodied exergy input in six sectors were collected in Table 7.

3.1.3. E_R accounting

To evaluate comprehensively the environmental emission influences, we construct an inclusive framework for different types of embodied exergy interference originally from resource consumption, in which we choose the emissions with the most discharge can concern, as well as in consideration of data availability. The E_R accounting frame is shown in Fig. 4.

In this study, Greenhouse gas emission factors are from IPCC [51], and partly revised on account of China's energy structure and quality. In addition, with the limitation of precise and sectoral environmental data, we collect and sort all existing databases together exhibited in Tables 8-a, 8-b and 9. For the waste gas and water emissions, pollutants' exergy can be evaluated according to their chemical ingredients. However, the complexity of solid waste lists made it impossible to calculate emission exergy based on detailed account. Therefore, we use the embodied emission exergy (Method 2.3) to estimate this part. The accounting parameters used in this part are listed in Tables 8-a and 8-b and Table 9 is the integrated value of E_R.

Note: In China, waste water generated in Transportation and Tertiary sectors is statistically recorded in Domestic sector, and pollution control costs for solid waste pollution are only available in broad production sectors (Extraction, Conversion, and Industry for instance). For the other vacant sectors, data are blended with social capital input, making it hard to be certain all emissions are accounted. Likely, the overall method underestimates the emissions and required exergy to remediate them.

Table 4
E_{in} input in EX, CO and AG sectors.

E_{in} items	Exergy conversion coefficient	Coefficient unit	Yield (PJ)	Export (PJ)	Import (PJ)	E_{in} input (PJ)
EX-sector						
Raw coal	22.16	PJ/Mton	5.60E+04	1.25E+03	1.16E+03	5.59E+04
Crude oil	44.32	PJ/Mton	8.26E+03	3.83E+01	6.32E+01	8.28E+03
Natural gas	4.13	PJ/10^8cu.m	2.86E+03	1.07E+02	1.66E+02	2.92E+03
Net import-export/PJ						
Copper	1.1	PJ/Mton	4.29E+00	1.001		5.29E+00
Aluminum	2	PJ/Mton	3.02E+01	0.4		3.06E+01
Lead	0.02	PJ/Mton	5.80E−02	0.003		6.10E−02
Zinc	0.05	PJ/Mton	2.02E−01	–		2.02E−01
Nickel	4	PJ/Mton	1.00E+00	0.488		1.49E+00
Tin	3	PJ/Mton	4.62E−01	0.024		4.86E−01
Iron	0.42	PJ/Mton	3.46E+02	159.6252		5.06E+02
Steel	6.8	PJ/Mton	7.38E+03	−287.98		7.10E+03
Phosphorus minerals	0.1	PJ/Mton	5.07E+00			5.07E+00
Crude salt	0.2	PJ/Mton	1.19E+01			1.19E+01
CO-sector	Exergy conversion coefficient (calorific value calculation)		Coefficient unit	Yield unit	Yield amount	E_{in} input (PJ)
Hydro Power	0.36		PJ/10^8 kW h	10^8 kW h	5963.89	2.15E+03
Nuclear Power	0.36		PJ/10^8 kW h	10^8 kW h	621	2.24E+02
AG-sector	Exergy conversion coefficient	Coefficient unit	Yield (PJ)	Export (PJ)	Import (PJ)	E_{in} input (PJ)
Rice	15.8	PJ/Mton	3.03E+05	1.53E+03	5.21E+02	3.02E+05
Wheat	13.9	PJ/Mton	1.56E+05		1.56E+03	1.58E+05
Corn	8.6	PJ/Mton	1.43E+05	2.32E+02	4.30E+01	1.42E+05
Beans	3.9	PJ/Mton	7.97E+03	1.83E+02	1.46E+04	2.24E+04
Tubers	3.3	PJ/Mton	9.83E+03			9.83E+03
Peanuts	24.6	PJ/Mton	3.51E+04	5.66E+02		3.46E+04
Rapeseeds	37	PJ/Mton	4.48E+04	3.26E+03	3.26E+04	7.41E+04
Sesame	29	PJ/Mton	1.70E+03			1.70E+03
Cotton and fiber crops	16.4	PJ/Mton	1.33E+04	2.62E+01	3.46E+03	1.67E+04
Sugarcane and beetroots	5	PJ/Mton	6.71E+04	2.90E+01	3.90E+02	6.75E+04
Tea and tobacco	10.7	PJ/Mton	4.38E+03	4.42E+02	2.40E+01	3.96E+03
Silkworm cocoons	4.5	PJ/Mton	4.09E+02			4.09E+02
Fruits	1.9	PJ/Mton	3.65E+04	5.42E+02	3.25E+02	3.63E+04
Timber	8	PJ/Mton	9.99E+01		5.69E+01	1.57E+02
Meat	4.6	PJ/Mton	3.35E+04	3.34E+02		3.31E+04
Milk	4.9	PJ/Mton	1.85E+04			1.85E+04
Poultry eggs	6.1	PJ/Mton	1.65E+04	3.71E+00		1.65E+04
Wool and Cashmere	3.7	PJ/Mton	1.59E+03	1.19E+01	1.07E+02	1.68E+03
Aquatic products	5.8	PJ/Mton	2.84E+04	1.02E+03	1.04E+03	2.84E+04

Table 5
CEC-1 accounting based on E_{in} consumption in seven sectors.

Sectors	E_{in} items	E_{in} consumption	Consumption unit	Exergy of E_{in} consumption (PJ)
EX-sector	Coal	1.77E+04	10^4 ton	3.91E+03
	Coke	2.17E+02	10^4 ton	6.48E+01
	Crude oil and oil products	1.65E+03	10^4 ton	7.30E+02
	Natural gas	9.63E+01	10^8 cu m	3.98E+02
	Electricity	1.61E+03	10^8 kW h	5.81E+02
CO-sector	Coal	1.32E+05	10^4 ton	2.92E+04
	Coke	7.35E+00	10^4 ton	2.19E+00
	Crude oil and oil products	9.01E+02	10^4 ton	3.99E+02
	Natural gas	7.08E+01	10^8 cu m	2.92E+02
	Electricity	4.64E+03	10^8 kW h	1.67E+03
AG-sector	Coal	2.94E+03	10^4 ton	6.51E+02
	Coke	1.61E+01	10^4 ton	4.80E+00
	Crude oil and oil products	1.69E+02	10^4 ton	7.48E+01
	Natural gas	2.91E+00	10^8 cu m	1.20E+01
	Electricity	6.34E+02	10^8 kW h	2.28E+02
IN-sector	Coal	2.91E+04	10^4 ton	6.44E+03
	Coke	3.27E+04	10^4 ton	9.75E+03
	Crude oil and oil products	6.29E+04	10^4 ton	2.79E+04
	Natural gas	3.24E+02	10^8 cu m	1.34E+03
	Electricity	1.63E+04	10^8 kW h	5.86E+03
TR-sector	Coal	6.85E+02	10^4 ton	1.52E+02
	Coke	5.50E−01	10^4 ton	1.64E−01
	Crude oil and oil products	1.22E+04	10^4 ton	5.43E+03
	Natural gas	1.69E+01	10^8 cu m	6.98E+01
	Electricity	5.32E+02	10^8 kW h	1.91E+02
TE-sector	Coal	8.10E+03	10^4 ton	1.80E+03
	Coke	7.64E+01	10^4 ton	2.28E+01
	Crude oil and oil products	6.59E+02	10^4 ton	2.92E+02
	Natural gas	1.33E+02	10^8 cu m	5.51E+02
	Electricity	3.62E+03	10^8 kW h	1.30E+03
DO-sector	Coal	1.97E+04	10^4 ton	4.37E+03
	Coke	2.25E+03	10^4 ton	6.70E+02
	Crude oil and oil products	3.50E+03	10^4 ton	1.55E+03
	Natural gas	3.53E+01	10^8 cu m	1.46E+02
	Electricity	2.95E+03	10^8 kW h	1.06E+03
	Rice	1.91E+04	10^6 ton	3.02E+05
	Wheat	1.14E+04	10^6 ton	1.58E+05
	Corn	1.66E+04	10^6 ton	1.42E+05
	Beans	5.74E+03	10^6 ton	2.24E+04
	Tubers	2.98E+03	10^6 ton	9.83E+03
	Peanuts	1.41E+03	10^6 ton	3.46E+04
	Rapeseeds	2.00E+03	10^6 ton	7.41E+04
	Sesame	5.86E+01	10^6 ton	1.70E+03
	Cotton and fiber crops	1.02E+03	10^6 ton	1.67E+04
	Sugarcane and beetroots	1.35E+04	10^6 ton	6.75E+04
	Tea and tobacco	3.71E+02	10^6 ton	3.96E+03
	Silkworm cocoons	9.09E+01	10^6 ton	4.09E+02
	Fruits	1.91E+04	10^6 ton	3.63E+04
	Timber	1.96E+01	10^6 ton	1.57E+02
	Meat	7.21E+03	10^6 ton	3.31E+04
	Milk	3.78E+03	10^6 ton	1.85E+04
	Poultry eggs	2.70E+03	10^6 ton	1.65E+04
	Wool and Cashmere	4.55E+02	10^6 ton	1.68E+03
	Aquatic products	4.90E+03	10^6 ton	2.84E+04

3.2. Extended exergy input–output relationships among seven sectors

Fig. 5 demonstrates the complete extended exergy flows for the seven sectors based on an input–output view. From the exergy values labeled in the pictures, it is explicitly showed that the basic sectors, Extraction, Conversion, and Agriculture, have direct input from ecological resources, *CEC-2* input from the other five sectors into one certain sector, E_L and E_K inputs from Domestic sector, environmental influences based on material resource depletions as well. The Domestic sector plays the part as a labor provider and capital creator, so all the input and output embodied exergy through this sector are related with substantial base flows. Moreover, for the other sectors, they consumed the primary resources after the elementary manufacture in basic sectors, secondary products and services from other parts, as well as the social-economic input from Domestic sector. All the embodied exergy input–output flows, with various sources, different directions among seven sectors are summarized in Fig. 5.

Table 6-a
CEC-2 accounting based on IO Table for currency flows among seven sectors (Unit: 104 RMB).

	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector
EX-sector	–	–	7.81E+05	7.47E+07	1.22E+07	1.97E+07
CO-sector	–	–	2.48E+08	2.86E+09	1.48E+08	3.23E+08
AG-sector	–	–	6.88E+07	9.76E+07	7.97E+06	2.30E+07
IN-sector	–	–	5.71E+03	5.11E+07	4.00E+06	2.65E+07
TR-sector	–	–	3.80E+06	1.05E+08	2.26E+07	3.77E+07
TE-sector	–	–	2.17E+07	3.42E+08	5.62E+07	2.71E+08
DO-sector	–	–	–	3.00E+07	2.41E+07	4.34E+08

Table 6-b
CEC-2 accounting based on IO Table for exergy flows among seven sectors (Unit: PJ).

	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector
EX-sector	–	–	6.53E+01	6.25E+03	1.02E+03	1.64E+03
CO-sector	–	–	2.08E+04	2.39E+05	1.24E+04	2.70E+04
AG-sector	–	–	5.75E+03	8.16E+03	6.67E+02	1.92E+03
IN-sector	–	–	4.78E−01	4.27E+03	3.35E+02	2.22E+03
TR-sector	–	–	3.17E+02	8.75E+03	1.89E+03	3.15E+03
TE-sector	–	–	1.81E+03	2.86E+04	4.70E+03	2.26E+04
DO-sector	–	–	–	2.51E+03	2.02E+03	3.63E+04

Table 7
Original sectoral data and final human embodied exergy input in six sectors.

Sectors	Employed population (million)	Average salary (RMB/(person × yr))	E_L (PJ)	E_K (PJ)
EX-sector	1.89E+01	28046.73	1.58E+03	7.72E+02
CO-sector	1.07E+01	33378.38	8.99E+02	4.38E+02
AG-sector	3.21E+02	10898.43	2.70E+04	1.31E+04
IN-sector	1.59E+02	20343.21	1.34E+04	6.51E+03
TR-sector	2.20E+01	27730.70	1.85E+03	8.99E+02
TE-sector	2.55E+02	27717.60	2.14E+04	1.04E+04

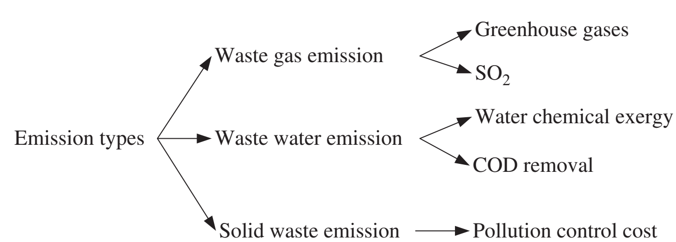

Fig. 4. The E_R accounting frame for environmental emissions in China.

3.3. Total extended exergy flow in seven sectors, network relationship and analysis

Based on the decomposed extended exergy allocations within the seven sectors in Section 3.2, a general extended exergy distribution flow matrix is constructed in Table 10. Meanwhile, in order to vividly reveal the flow disparity, we construct a sectoral metabolism hierarchical network of the social-economic consumption system on account of extended exergy distribution flows (see Fig. 6).

In this figure, Z represents the E_{in} input directly from natural resources; Y is the output of sector containing environmental emission exergy and unemployed exergy emission; f_{ij} means exergy flow from j sector into i sector. Full lines refer to exergy flow based on material resource delivered among different sectors, dotted lines are labor and capital exergy which are the production of Domestic sector after substantial resource consumption.

3.4. Indicators analysis

3.4.1. Extended exergy in sectoral allocation

Fig. 7 clearly indicates: (1) Conversion and Domestic are the largest two sectors for *CEC* consumption, in which Domestic is the final material based expenditure sector for the sake of supporting basic human survival and development; however, in Conversion more than 65% of the electricity in 2007 [41] was generated from fossil fuels, which is determined by energy structure in China. (2) Labor is concentrated in the Agriculture, Industrial and Tertiary sectors, employing more than 93% of the population in 2007. (3) The Agriculture and Tertiary sectors need more than 73% of the supporting embodied exergy capital. Therefore, from Fig. 7b and c, Agriculture and Tertiary are labor and fund intensive sectors. To optimize the existing manpower structure in China, Agriculture and Tertiary are the key sectors for regulation. (4) Transportation sector generates the largest amount of environmental emission exergy. Compared with its *CEC* consumption, it is obvious that Transportation has a low efficiency of environment friendly input–output ratio for energy use.

Table 8-a
Accounting parameters used in E_R evaluation.

Items	Unit	Revised green gas emission factors
Coal	kg CO_2/kg	2.21
Crude oil	kg CO_2/kg	3.4
Natural gas	kg CO_2/m^3	2.88
Electricity	kg CO_2/MJ	0.19
Items	Unit	Standard chemical exergy (ScEx)
CO_2	kJ/kg	451.6
NO_x	kJ/kg	2963.3
SO_2	kJ/kg	4892.3
COD	PJ/Mt	13.6
Water	kJ/kg	50 kJ/kg

Table 8-b
Sectoral emissions of SO_2 and NO_X in China (2007).

Sector	SO_2 emission (10,000 ton)	NO_X emission (10,000 ton)
EX-sector	51.04	1.89E+02
CO-sector	1149.74	1.34E+03
AG-sector	2.94E+03	–
IN-sector	771.46	9.83E+02
TR-sector	6.88E+02	9.31E+04
TE-sector	1.97E+04	3.76E+01
DO-sector	8.12E+03	2.53E+01

3.4.2. Extended exergy efficiency metrics

(1) *Resource exergy efficiency metrics* (Fig. 8): In this picture, both the Agriculture and Tertiary sectors have high levels of *CEC-2* rate and E_R proportion compared with *CEC-1*, showing that in these two sectors, a large amount of secondary exergy investment plays an extremely important role in supporting the regular production and operation activities. Meanwhile, in these two sectors, a high percentage of environmental emissions based on *CEC-1* consumption are emitted into the surroundings, implying the low environmental efficiency and high pollution states. Meanwhile, for Conversion sector in China, plenty of *CEC-2* is fossil fuels for thermoelectric generation, therefore, the *CEC-2*/*CEC-1* ratio has a high value, but the environmental emission of secondary energy is accounted as the indirect emission of final consumption sector as shown in the EEA accounting boundary in Fig. 1, for example, Tertiary sector exhausts the electricity, it is Tertiary not Conversion sector should take responsibility for the emission of this electricity generation. Thus, emission exergy in Conversion is lower than that in Agriculture and Tertiary, due to its emission burdens are distributed into the other final consumer sectors. Furthermore, in Industrial and Domestic sectors, they exceedingly depend on *CEC-1* depletion. For Domestic is mainly consuming agriculture products for human survival, but Industry is principally depleting primary or non sustainable resources, though the environmental emission rate is low, the total amount of environmental disturbance is considerable.

(2) *Exergy output/input efficiency metrics: Exergy output/Exergy input*: Here the exergy input and output results are gained in Section 3.2 of the extended exergy input–output relationships. In Fig. 9, Agriculture, Industry, Transportation and Tertiary have nearly full value of output–input ratio, demonstrating them as almost pure exergy carriers or transmitters

Table 9
The integrated value of E_R.

Sector	CO_2 (PJ)	SO_2 (PJ)	NO_x (PJ)	Waste water (PJ)	Solid waste emission exergy (PJ)	Environmental emission (PJ)
EX-sector	2.66E+02	2.50E+00	5.59E+00	2.48E+00	2.45E+00	2.71E+02
CO-sector	1.35E+03	5.62E+01	3.97E+01	1.24E+00	9.76E−01	1.44E+03
AG-sector	3.41E+01	1.44E+02	–	6.95E+01	–	2.47E+02
IN-sector	1.64E+03	3.77E+01	2.91E+01	5.80E+01	7.18E−01	1.77E+03
TR-sector	1.96E+02	3.37E+01	1.13E+01	–	–	2.41E+02
TE-sector	2.82E+02	9.65E+02	1.12E+00	–	–	1.25E+03
DO-sector	3.50E+03	3.97E+02	7.50E−01	1.18E+02	–	4.01E+03

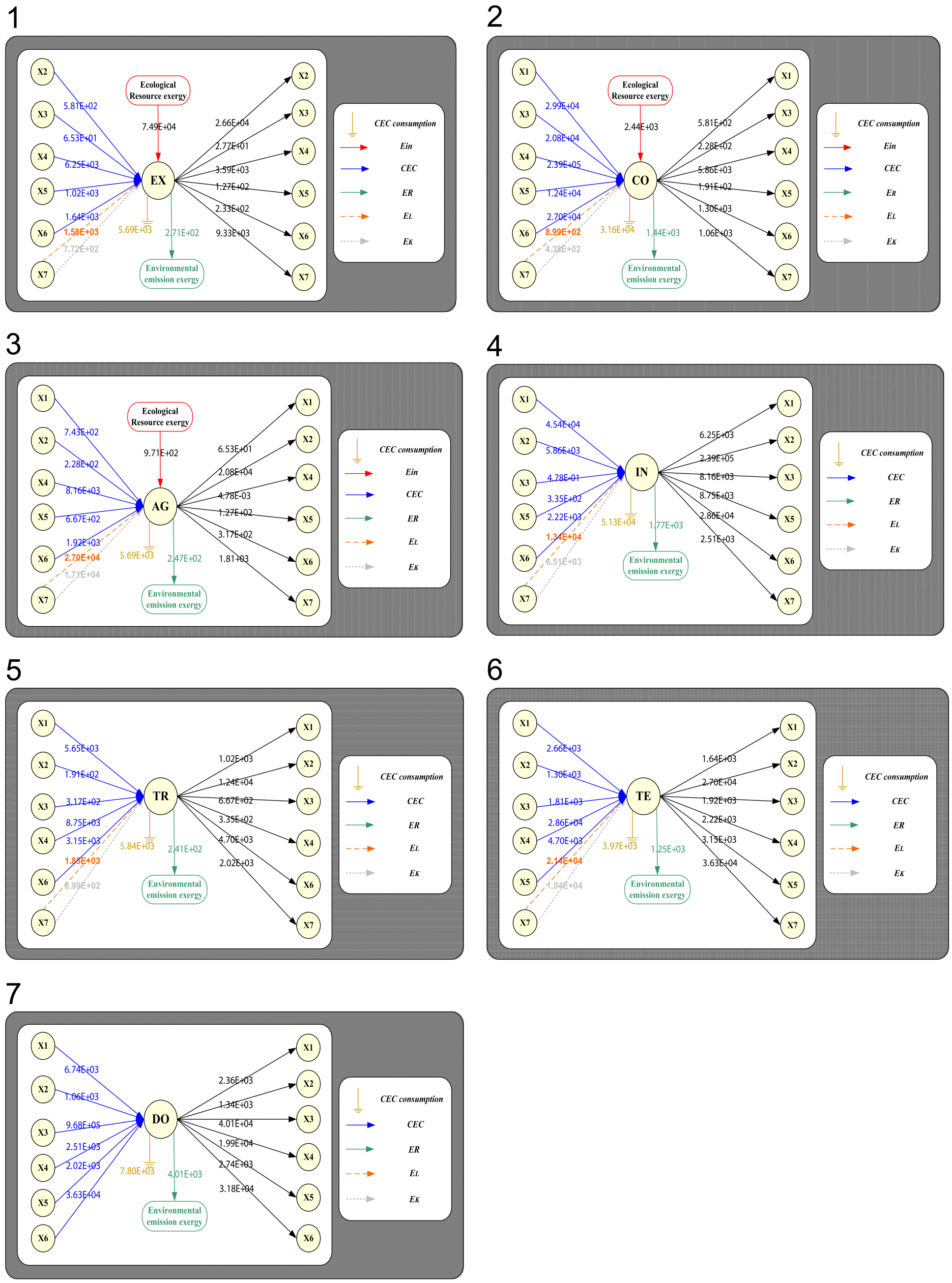

Fig. 5. Extended exergy input–output relationships in seven sectors where X1: Extraction; X2: Conversion; X3: Agriculture; X4: Industry; X5: Transportation; X6: Tertiary; X7: Domestic, Unit: PJ. (1) EX-sector. (2) CO-sector. (3) AG-sector. (4) IN-sector. (5) TR-sector. (6) TE-sector. (7) DO-sector.

Table 10
Extended exergy based distribution flow matrix in seven sectors.

j sector	*i* sector							
	Resource input	EX-sector	CO-sector	AG-sector	IN-sector	TR-sector	TE-sector	DO-sector
EX-sector	7.70E+04	5.11E+03	5.81E+02	6.53E+01	6.25E+03	1.02E+03	1.64E+03	2.36E+03
CO-sector	2.44E+03	2.99E+04	1.67E+03	2.08E+04	2.39E+05	1.24E+04	2.70E+04	1.34E+03
AG-sector	9.96E+05	7.43E+02	2.28E+02	5.75E+03	8.16E+03	6.67E+02	1.92E+03	4.01E+04
IN-sector	–	4.54E+04	5.86E+03	4.78E−01	4.27E+03	3.35E+02	2.22E+03	1.99E+04
TR-sector	–	5.65E+03	1.91E+02	3.17E+02	8.75E+03	1.89E+03	3.15E+03	2.74E+03
TE-sector	–	2.66E+03	1.30E+03	1.81E+03	2.86E+04	4.70E+03	2.26E+04	3.18E+04
DO-sector	–	6.74E+03	1.06E+03	9.68E+05	2.51E+03	2.02E+03	3.63E+04	–
Environmental emission	–	2.74E+02	1.44E+03	2.47E+02	1.77E+03	2.41E+02	1.25E+03	4.01E+03

of the whole system. They use up a small amount of the input exergy within their own sectors, and then act as full exergy providers to next exergy acceptor after the their internal machining.

(3) *Social economic exergy proportion metrics*: $(E_L+E_K)/EE$: Fig. 10 shows the labor and capital input from the Domestic sector to the other sectors. It is pointed out the Agriculture and the Tertiary utilized the largest amount of labor and capital investments in the entire system. The extensive use of labor in these sectors implies that they offer the most potential in optimizing labor allocation. Particularly, this is of great concern for decision makers to facing the looming aging society with labor shortages.

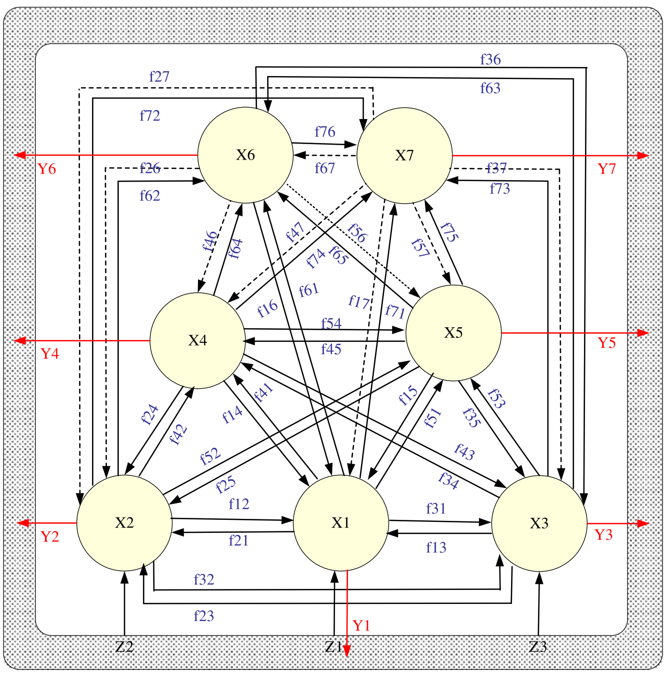

Fig. 6. Network relationships for sectoral metabolism hierarchical extended-exergy flows, where X1: Extraction; X2: Conversion; X3: Agriculture; X4: Industry; X5: Transportation; X6: Tertiary; X7: Domestic.

4. Conclusion

The thermodynamic concept of extended exergy (EEA) is introduced to unify the assessment of the different production sectors that contribute to the cost formation processes in the Chinese social-economic system in 2007.Once we accept to calculate "cost" on a physical basis, and to express it in units of exergy of consumed resources (expressed equivalently in the unit of Joules), EEA provides a scientific and objective measure for material resource input, labor and capital expenditures and physical remediation costs of environmental impacts. The four components of the extended exergy cost were calculated for seven aggregated sectors based on the 42 sector Input–Output Table. Our results show that: the interactions between economic sectors could be explained in the form of a network, which analogous to an ecological trophic structure; and primary resource sectors act as base for consumption of the socio-ecological trophic structure; furthermore, agriculture, industry, transportation, and tertiary sectors play as exergy carriers or transmitters of the entire social-economic system.

Another conclusion is that, different sectors need different strategies to become a more sustainable systemic pattern.

(1) *Particularly, for the Conversion sector*: on one side, it is urgent to lower the primary exergy input by regulating existing energy generation structure in China, decrease the thermal powered electricity, so as to reduce both natural resource consumption and environmental emissions; on the other side, it is necessary to advocate the development of cleaner energy, hydroelectric, wind power, tidal power etc., for instance, to replace nonrenewable energy and (or) exergy saving during the long-term sustainable developing process.

(2) *For Transportation sector*: it has the highest level of E_R emission. Transportation sector, basically depending on fossil sources, is one of the major contributors both to the energy

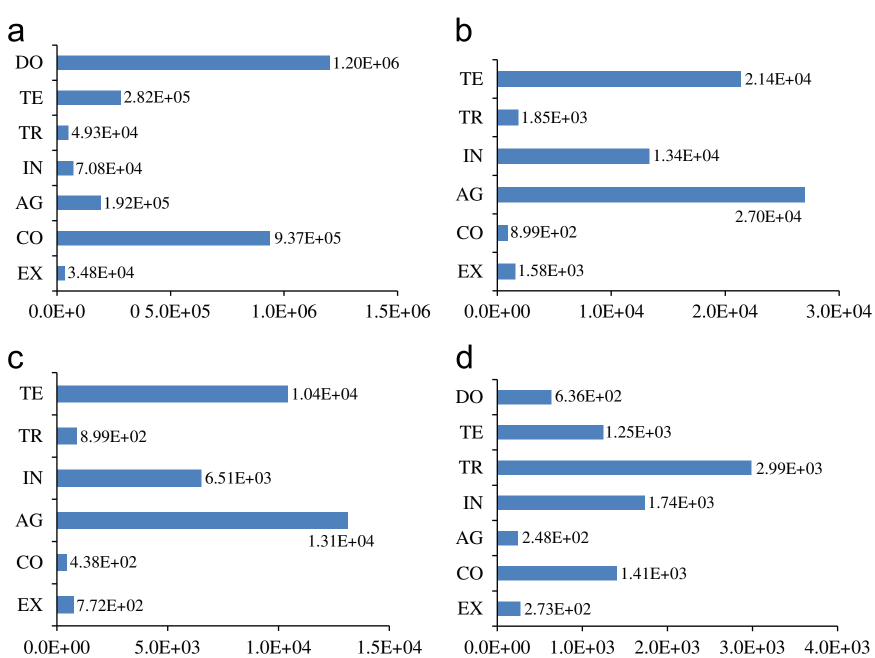

Fig. 7. Four parts of extended exergy allocation in seven sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic. (a) *CEC* consumption (PJ), (b) E_L emission (PJ), (c) E_K input (PJ) and (d) E_R input (PJ).

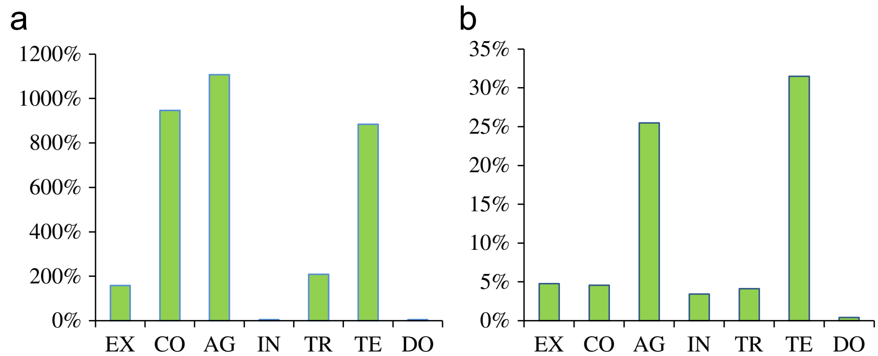

Fig. 8. Resource exergy efficiency metrics in seven sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic. (a) Secondary exergy use/Primary exergy use=CEC-2/CEC-1. (b) Emission remediation exergy/Resource exergy consumption= E_R/CEC-1.

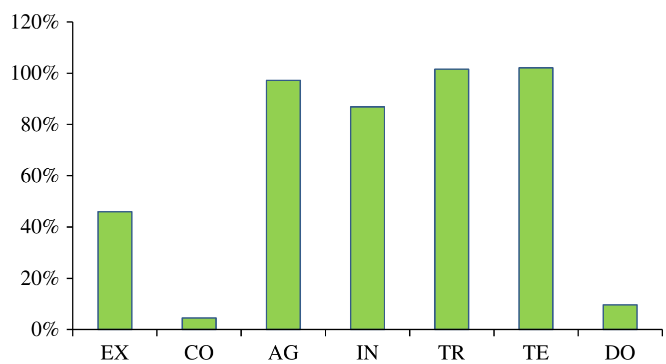

Fig. 9. Exergy output/input efficiency metrics in seven sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic.

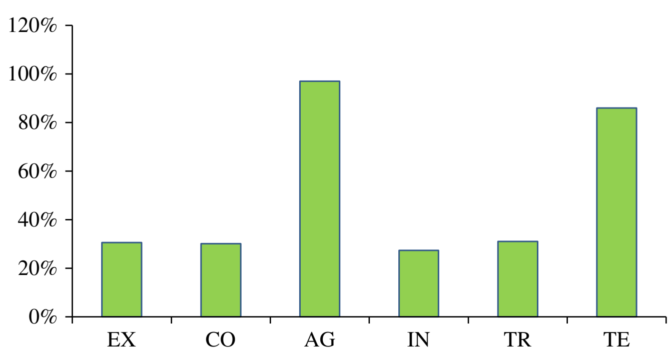

Fig. 10. Social economic exergy proportion metrics in six sectors where EX: Extraction; CO: Conversion; AG: Agriculture; IN: Industry; TR: Transportation; TE: Tertiary; DO: Domestic.

final use and to the GHG emissions. Specifically, as being vitally interrelated with industrial and social development and with life standards, it is producing ever higher environmental impacts as urban air pollution and as global warming caused by both direct emissions from fossil fuel consumption and indirect emissions due to the development of traffic infrastructures. Not surprisingly, there is no doubt Transportation sector has been the most important sector for policy makers to control environmental emissions by developing cleaner transport fuel substitution, optimizing traffic path arrangement, advocating energy saving travel modes, etc.

(3) *For the Agriculture and Tertiary sectors*: Human behavior dominates a severe influence in their regular operations. To make the transition from labor oriented to technical oriented mode, these two sectors should draw the most focus. Moreover, the coming aging era and fluctuation of labor force composition will firstly make impacts in Agriculture and Tertiary sector in China.

In addition, a very simple conclusion is that the previous stated method and results suggest that all current monetary methods strongly underestimate the environmental effects on both ends (extraction of resources and final disposal): i.e., the real impact of the Transportation sector is definitely worse than what the standard analyses demonstrate! For example, long term ecological impacts on biodiversity, climate change, and ecological degradation cannot be interpreted only by extended exergy accounting in social-economic system. That would be the next largest problem for further exploration. However, what is important is to realize that any "ecological viewpoint" in evaluation the human influence on ecological resource consumption must be founded on a cost measure quantified by the physical or eco-thermodynamic metric of resources consumption rather than by monetary proxies thereof.

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